January 19th, 2024

A fate of catalyzed first order phase transition -black holes from primordial black holes-

TAsP meeting @ Università di Torino

Università degli Studi di Padova

Jun’ya Kume (UNIPD, INFN, RESCEU)

INFN Padova
Istituto Nazionale di Fisica Nucleare
Sezione di Padova

RESEARCH CENTER FOR THE EARLY UNIVERSE
THE UNIVERSITY OF TOKYO
RESCEU

Based on arXiv:2310.06901 [hep-ph] (to appear in PLB)

with Ryusuke Jinno (RESCEU), Masaki Yamada (Tohoku U.)

Contents

- Cosmological FOPT & gravitational waves
- Sparsely distributed PBHs as impurities
- SGWB from bubble collision & baby BH constraints
- Summary & Discussion

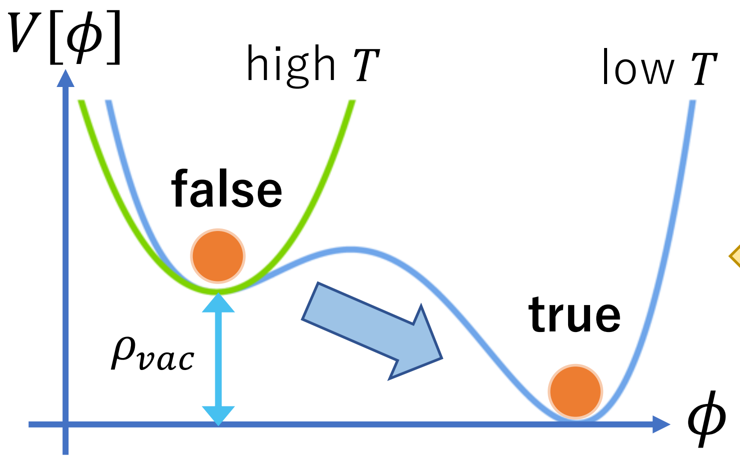
Cosmological phase transition & gravitational waves

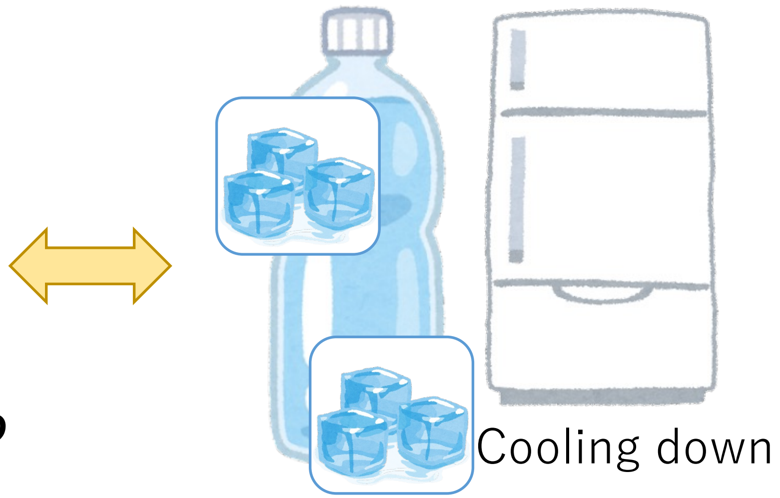
- Cosmological FOPT

microscopic: quantum tunneling of a “Higgs” field ϕ

various realization in **BSM**

→ ”bubble” nucleation in real space.





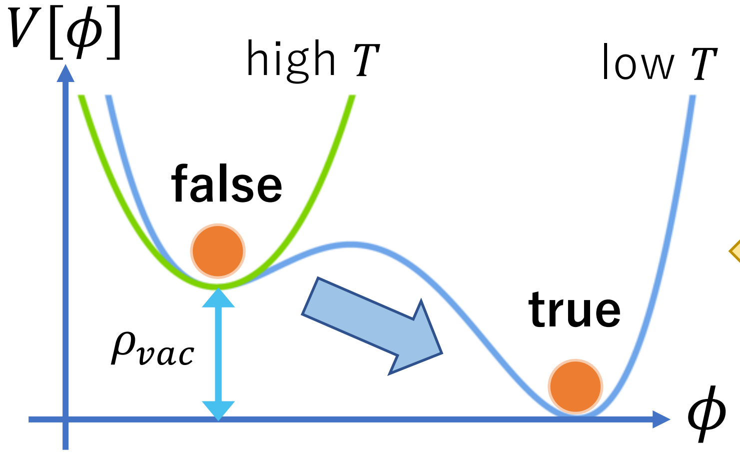
Cosmological phase transition & gravitational waves

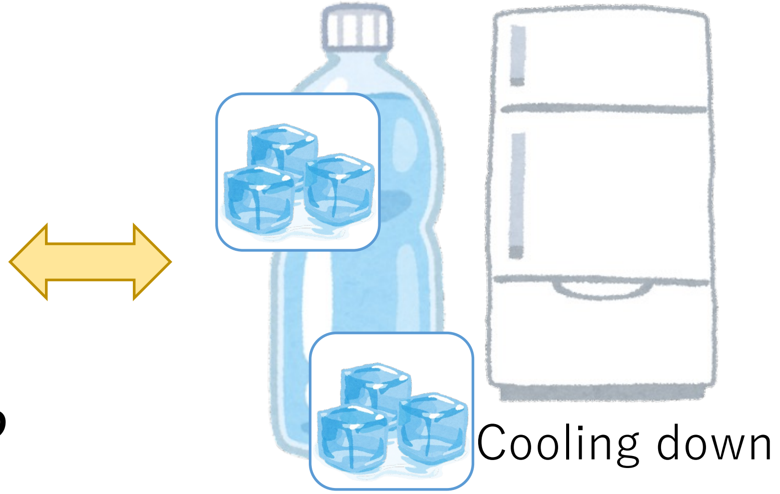
- Cosmological FOPT

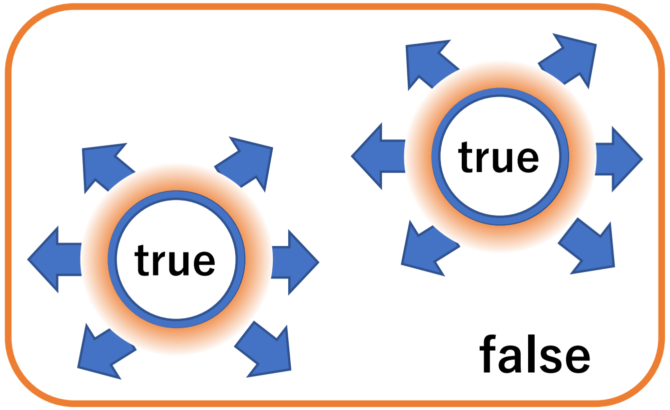
microscopic: quantum tunneling of a “Higgs” field ϕ

various realization in **BSM**

→ ”bubble” nucleation in real space.



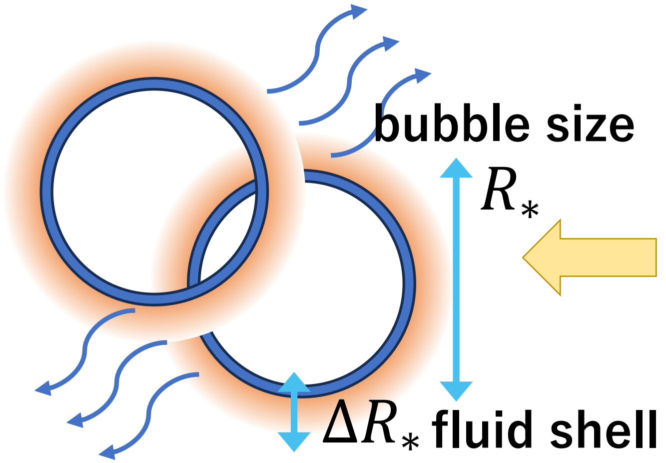




non-equilibrium → baryogenesis

macroscopic: bubbles stir plasma → Bubble + fluid dynamics sources **SGWB!**

- GW production in FOPT (Caprini+ 2019, Hindmarsh+ 2020, …)



Macroscopic parameters:

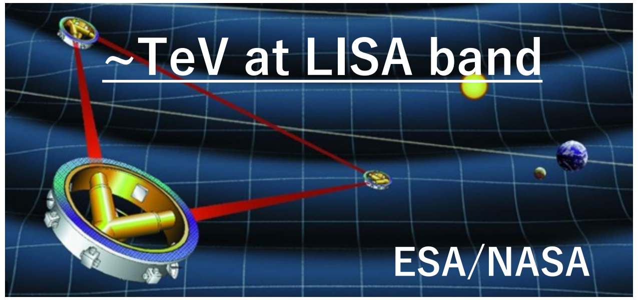
α: strength of PT v_w: wall velocity
β: $\simeq$ (PT duration)$^{-1}$
T_*: temperature at GW production

underlying theory?
$\mathcal{L}[\phi, \psi \ldots]$

✓**collision of walls**: relevant for large bubble

✓**sound waves**: dominant for fast transition

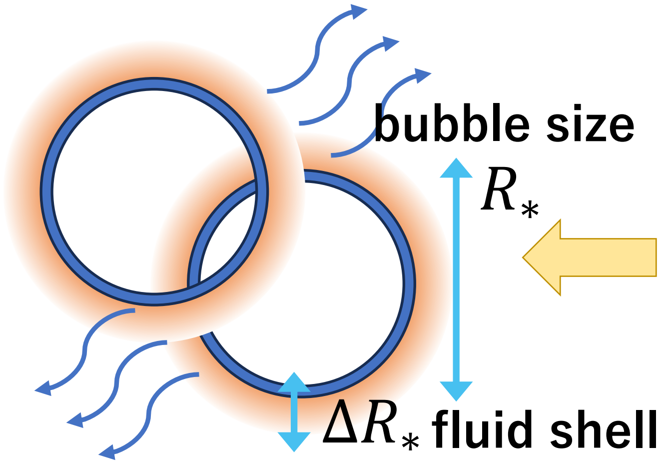
✓turbulence: for stronger PT? Yet to be simulated…



$H^{-1}(T_*) \Leftrightarrow R_* \Leftrightarrow$ GW freq.: f^{-1}

Observability…?

- GW production in FOPT (Caprini+ 2019, Hindmarsh+ 2020, ...)



Macroscopic parameters:

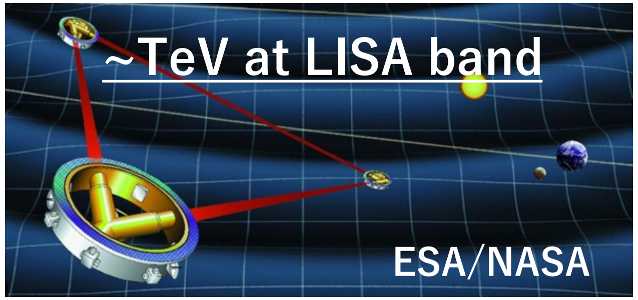
α: strength of PT v_w: wall velocity
β: $\simeq$ (PT duration)$^{-1}$
T_*: temperature at GW production

underlying theory?
$\mathcal{L}[\phi, \psi \ldots]$

✓**<u>collision of walls</u>**: relevant for <u>large bubble</u>

✓**<u>sound waves</u>**: dominant for fast transition

✓turbulence: for stronger PT? Yet to be simulated...



$H^{-1}(T_*) \Leftrightarrow R_* \Leftrightarrow$ GW freq.: f^{-1}

Observability...?

An interesting realization of large SGWB signal!

Contents

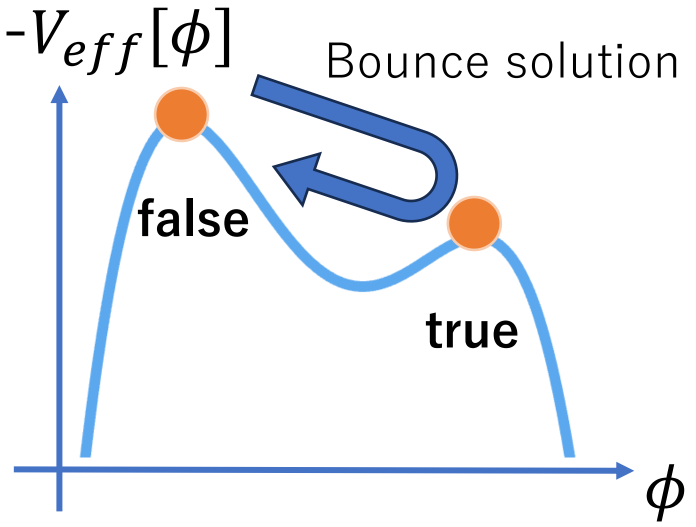
- Cosmological FOPT & gravitational waves
- Sparsely distributed PBHs as impurities
- SGWB from bubble collision & baby BH constraints
- Summary & Discussion

Sparsely distributed PBHs as impurities

- Bubble nucleation with compact objects

tunneling rate in QFT (cf. WKB approx. in QM)

$\Gamma = Ae^{-B}$ $B[\phi]$: Euclidian bounce action



Sparsely distributed PBHs as impurities

- Bubble nucleation with compact objects

tunneling rate in QFT (cf. WKB approx. in QM)

$\Gamma = Ae^{-B}$ $B[\phi]$: Euclidian bounce action

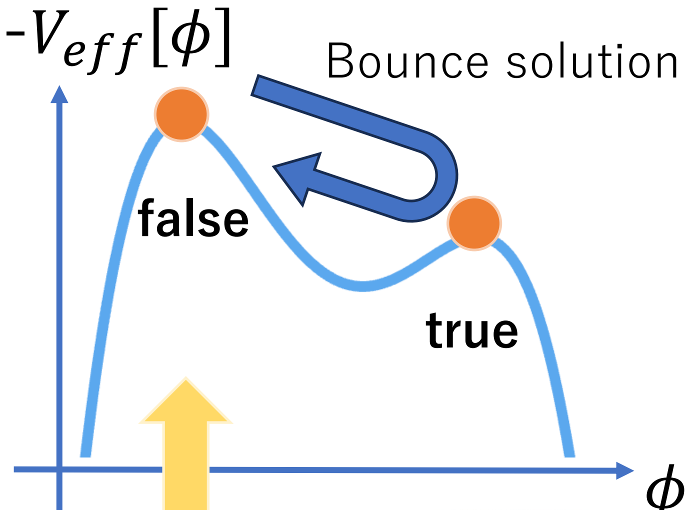
$V_{eff}[\phi]$ distorted by BHs, monopoles, solitons...

→ exponential enhancement in Γ !! (Hiscock 1987, ...)

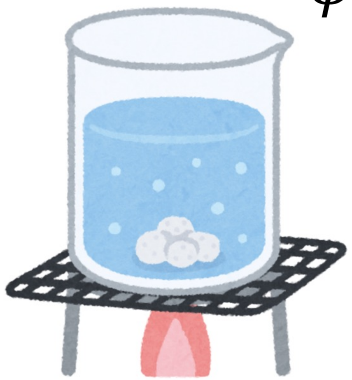
※"Thermal effect" is under debate for BHs (Gregory+ 2014, ...)

Gravitational distortion becomes efficient when

(Bubble radius) ~ (Schwarzschild radius) ~ (radius of object)



boiling chips



Sparsely distributed PBHs as impurities

- Bubble nucleation with compact objects

tunneling rate in QFT (cf. WKB approx. in QM)

$\Gamma = Ae^{-B}$ $B[\phi]$: Euclidian bounce action

$V_{eff}[\phi]$ distorted by BHs, monopoles, solitons...

→ exponential enhancement in Γ !! (Hiscock 1987, ...)

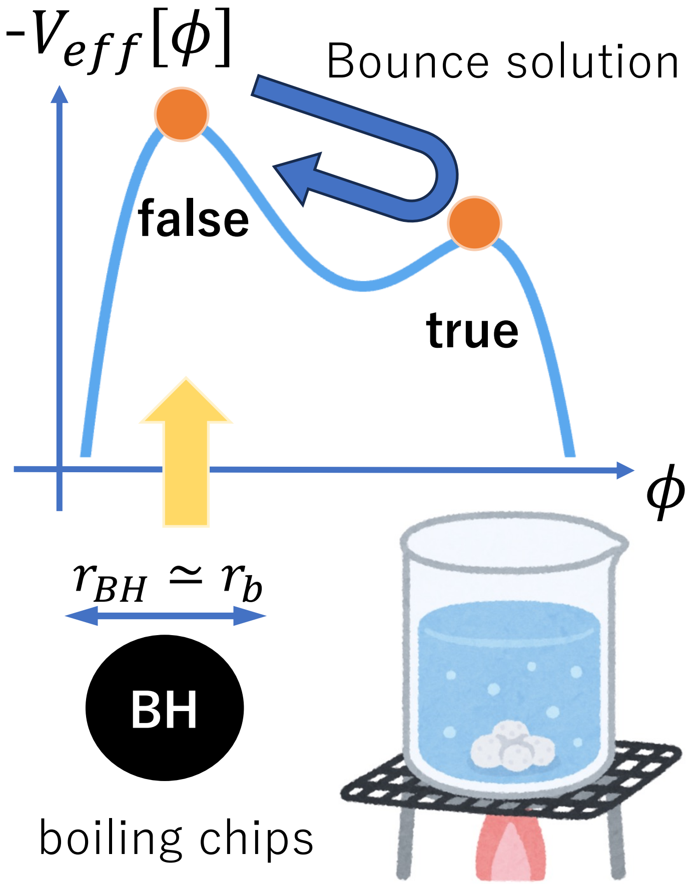
※"Thermal effect" is under debate for BHs (Gregory+ 2014, ...)

Gravitational distortion becomes efficient when

(Bubble radius) ~ (Schwarzschild radius) ~ (radius of object)

particle physics scale

Small PBH as nucleation site!!



- Super-slow FOPT with sparse PBHs

Requirement for particle sector:(※not specify a model)

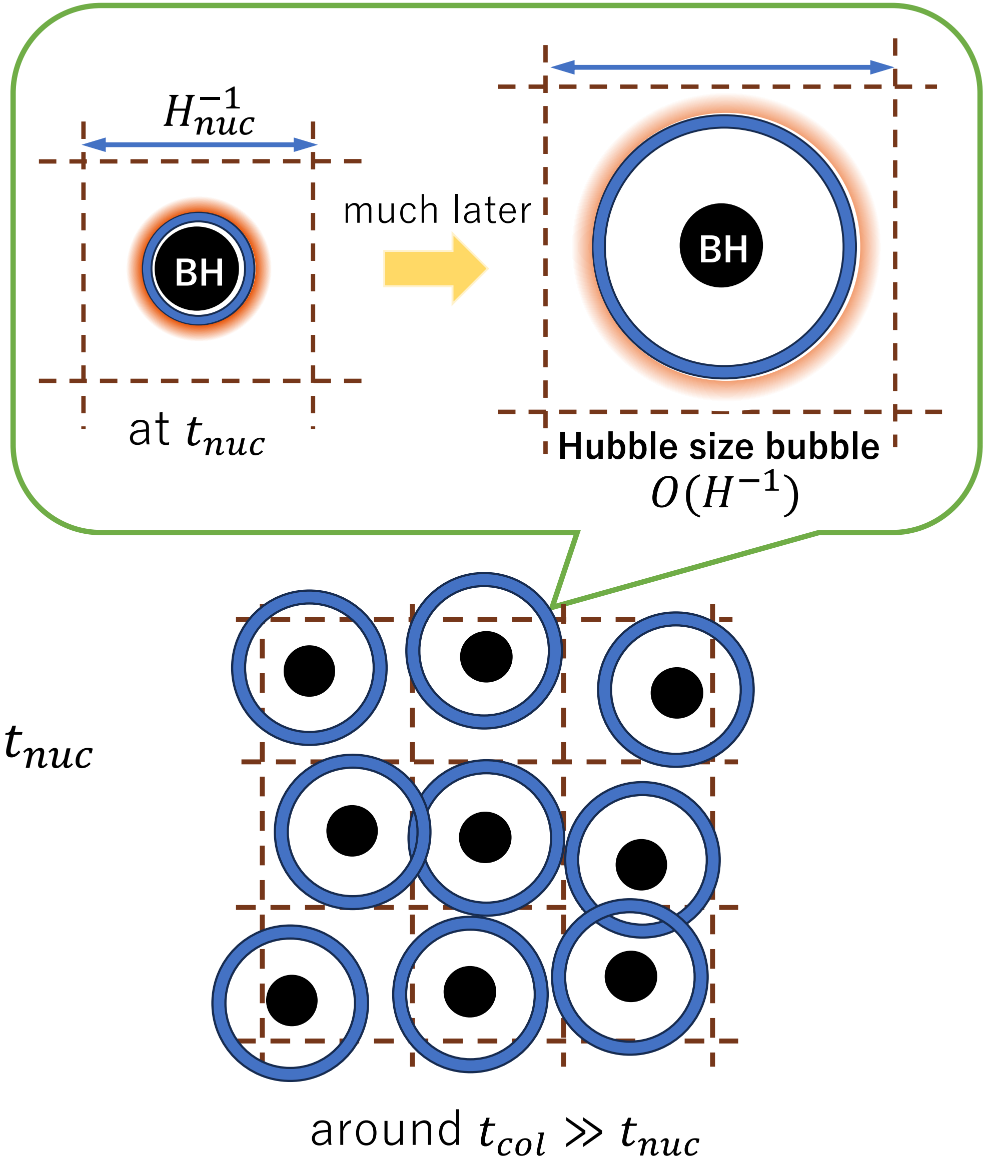
- $\Gamma_{w/BH}/H|_{t_{nuc}} \sim 1$ while $\Gamma_{w/o\,BH}/H \ll 1$
- FV – TV structure is maintained
  → PBHs serve as the bubble nucleation sites

Assumption on PBHs:

- Monochromatic mass $M_{PBH,i}$ formed at t_i
- $\epsilon(t) \equiv 3n_{PBH}(t)/4\pi^2 H^3(t) \ll 1$ at nucleation

  Bubble collision: $\epsilon(t_{col}) \sim 1 \rightarrow t_{col} \sim \epsilon^{-2/3} v_w^{-2} t_{nuc} \gg t_{nuc}$

  → bubble can expand until they reach to $O(H^{-1})$



- Super-slow FOPT with sparse PBHs

Requirement for particle sector: (※not specify a model)

・$\Gamma_{w/BH}/H|_{t_{nuc}} \sim 1$ while $\Gamma_{w/o\,BH}/H \ll 1$

・FV – TV structure is maintained

→ PBHs serve as the bubble nucleation sites

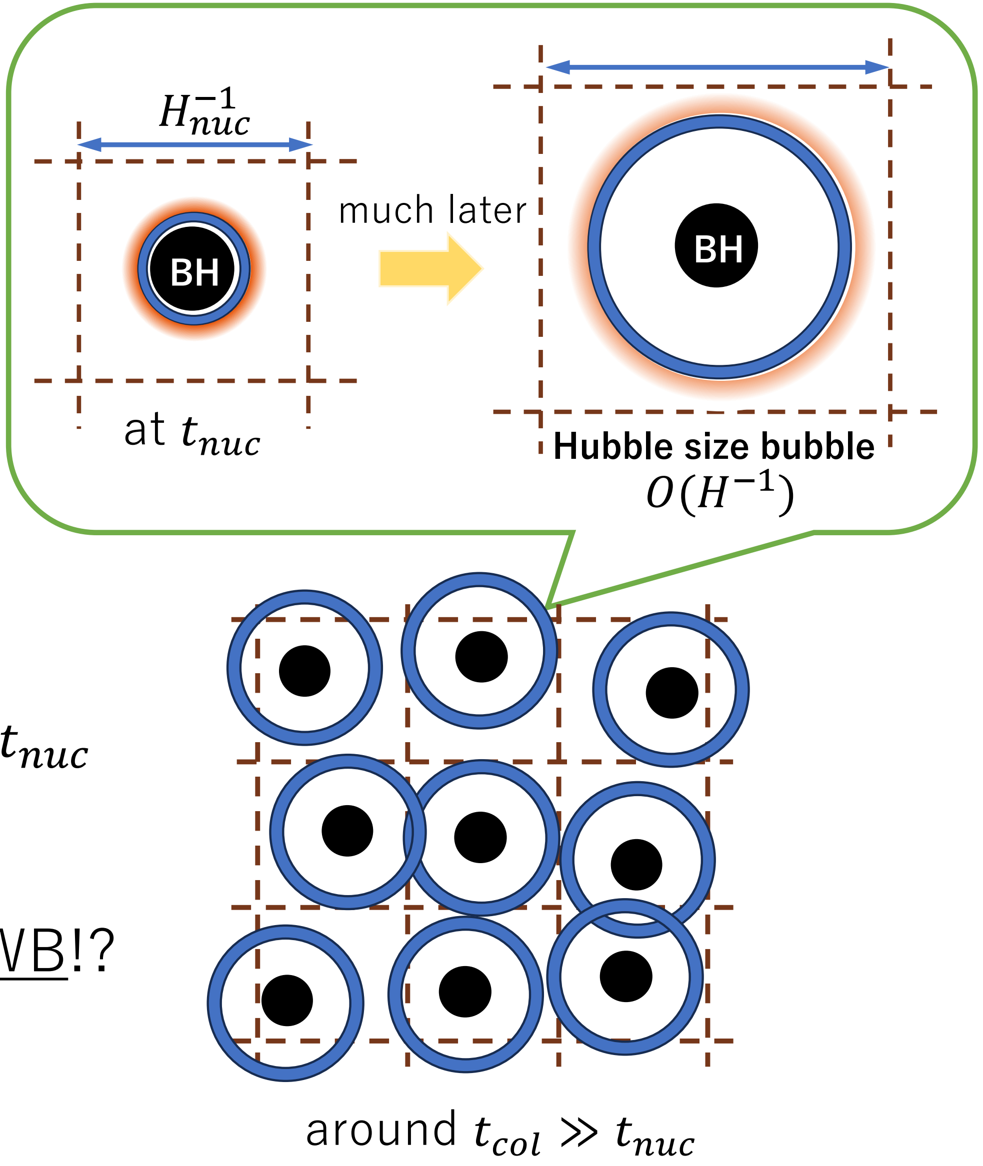
Assumption on PBHs:

・Monochromatic mass $M_{PBH,i}$ formed at t_i

・$\epsilon(t) \equiv 3n_{PBH}(t)/4\pi^2 H^3(t) \ll 1$ at nucleation

Bubble collision: $\epsilon(t_{col}) \sim 1 \rightarrow t_{col} \sim \epsilon^{-2/3} v_w^{-2} t_{nuc} \gg t_{nuc}$

→ bubble can expand until they reach to $O(H^{-1})$



Collision of large bubbles sources stronger SGWB!?

(El-Menoufi+ 2020, Jinno, **JK** & Yamada 2023)

※see our paper for quantitative discussion on FOPT dynamics

- Completion of slow FOPT and baby BHs (Jinno, **JK** & Yamada 2023)

Prob. for a point in FV: $P(t) = e^{-I(t)}$ $(\rightarrow I(t_{col}) \equiv 1)$

Growth in FV decay rate: $\beta(t) \equiv dlnP/dt = \dot{I}(t)$

For $\alpha(t_{col}) = \rho_{rad}(t_{col})/\rho_{vac} \ll 1$ (RD until $t_{eq} \sim \alpha_{col}^{-1/2} t_{col}$)

$\beta(t)/H(t) \sim 3I(t)$ with $I(t) \sim (t/t_{col})^{3/2}$

$\rightarrow$ $\boldsymbol{\beta_{col}/H_{col} \sim 3}$ & its growth ensures PT completion!!

$$I(t) = \frac{4\pi}{3}\int_0^t dt'\Gamma(t')a^3(t')r_{\text{bubble}}^3(t,t')$$

$$r_{\text{bubble}}(t,t') = v_b \int_{t'}^t \frac{dt''}{a(t'')}$$

In our scenario:

$\Gamma(t') = \delta(t' - t_{nuc})n_{PBH}(t_{nuc})$

$$\frac{d}{dt}\left(a^3(t)P(t)\right) < 0 \leftrightarrow \frac{\beta(t)}{H(t)} > 3$$

- Completion of slow FOPT and baby BHs (Jinno, **JK** & Yamada 2023)

Prob. for a point in FV: $P(t) = e^{-I(t)}$ $(\rightarrow I(t_{col}) \equiv 1)$

Growth in FV decay rate: $\beta(t) \equiv d\ln P/dt = \dot{I}(t)$

For $\alpha(t_{col}) = \rho_{rad}(t_{col})/\rho_{vac} \ll 1$ (RD until $t_{eq} \sim \alpha_{col}^{-1/2} t_{col}$)

$\beta(t)/H(t) \sim 3I(t)$ with $I(t) \sim (t/t_{col})^{3/2}$

→ $\boldsymbol{\beta_{col}/H_{col} \sim 3}$ & its growth ensures PT completion!!

$$I(t) = \frac{4\pi}{3}\int_0^t dt'\Gamma(t')a^3(t')r_{\rm bubble}^3(t,t')$$

$$r_{\rm bubble}(t,t') = v_b\int_{t'}^t \frac{dt''}{a(t'')}$$

In our scenario:

$\Gamma(t') = \delta(t' - t_{nuc})n_{PBH}(t_{nuc})$

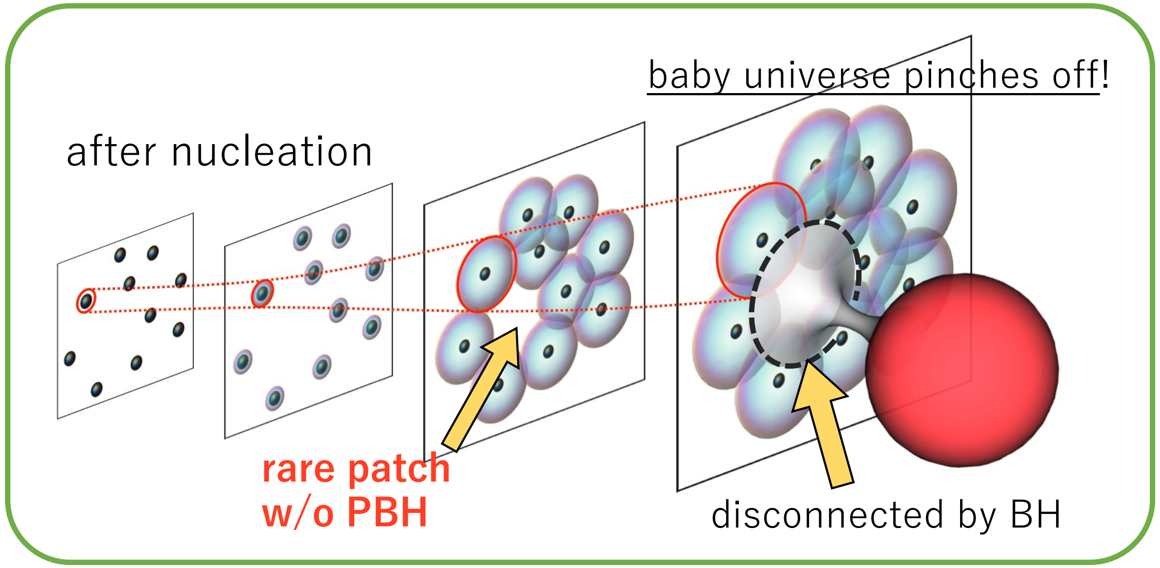
$$\frac{d}{dt}\left(a^3(t)P(t)\right) < 0 \leftrightarrow \frac{\beta(t)}{H(t)} > 3$$

This is not the end of the story!!

Rare patches w/o PBH start to inflate $t \sim t_{eq}$

→ causally disconnected by **"baby" BHs**

(cf. Garriga, Vilenkin & Zhang 2016)



- Completion of slow FOPT and baby BHs (Jinno, **JK** & Yamada 2023)

Prob. for a point in FV: $P(t) = e^{-I(t)}$ $(\to I(t_{col}) \equiv 1)$

Growth in FV decay rate: $\beta(t) \equiv d\ln P/dt = \dot{I}(t)$

For $\alpha(t_{col}) = \rho_{rad}(t_{col})/\rho_{vac} \ll 1$ (RD until $t_{eq} \sim \alpha_{col}^{-1/2} t_{col}$)

$\beta(t)/H(t) \sim 3I(t)$ with $I(t) \sim (t/t_{col})^{3/2}$

$\to$ $\boldsymbol{\beta_{col}/H_{col} \sim 3}$ & its growth ensures PT completion!!

$$I(t) = \frac{4\pi}{3}\int_0^t dt'\Gamma(t')a^3(t')r_{\rm bubble}^3(t,t')$$

$$r_{\rm bubble}(t,t') = v_b \int_{t'}^{t} \frac{dt''}{a(t'')}$$

In our scenario:

$\Gamma(t') = \delta(t' - t_{nuc})n_{PBH}(t_{nuc})$

$$\frac{d}{dt}\left(a^3(t)P(t)\right) < 0 \leftrightarrow \frac{\beta(t)}{H(t)} > 3$$

This is not the end of the story!!

Rare patches w/o PBH start to inflate $t \sim t_{eq}$

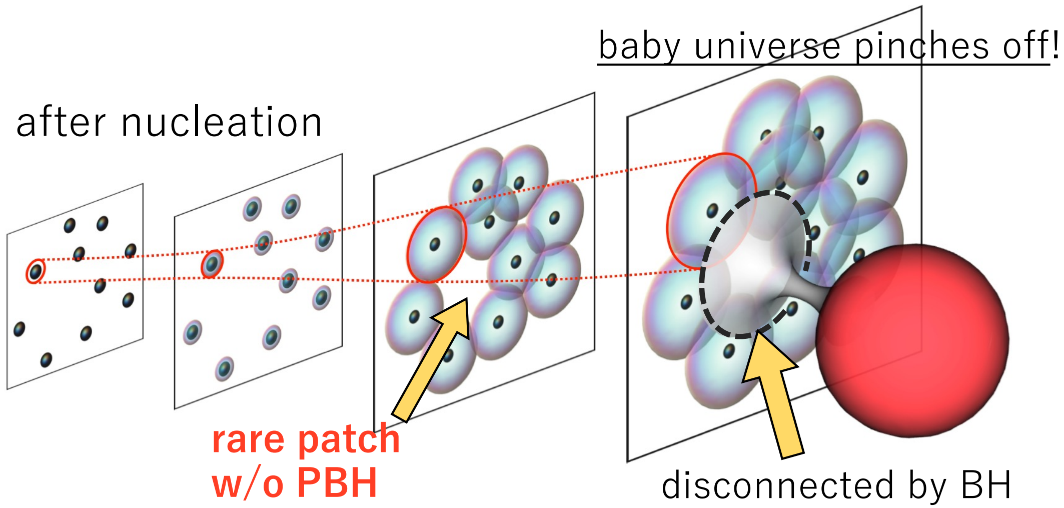
$\to$ causally disconnected by **"baby" BHs**

(cf. Garriga, Vilenkin & Zhang 2016)

mass: $M_{baby} \sim M_{pl}^2 H_{eq}^{-1} \sim M_{pl}^3 \rho_{vac}^{-1/2}$

abundance: depends on α_{col}

$\leftarrow$ bound from PBH constraints



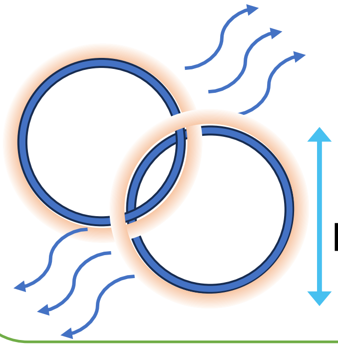
Contents

- ➢Cosmological FOPT & gravitational waves
- ➢Sparsely distributed PBHs as impurities
- ➢SGWB from bubble collision & baby BH constraints
- ➢Summary & Discussion

SGWB from Bubble collision & baby BH constraints

- SGWB from Bubble collision

$$\Omega_{gw}h^2 \sim 10^{-5}\left(\frac{H_{col}}{\beta_{col}}\right)^2\left(\frac{\kappa_\phi \alpha_{col}}{1+\alpha_{col}}\right)^2 \text{ with } f \sim 10^{-3}\left(\frac{\beta_{col}}{H_{col}}\right)\left(\frac{T_{col}}{10\text{TeV}}\right)$$



- In our scenario: $\beta_{col}/H_{col} \simeq 3$

diluted plasma → less friction: $v_w \sim 1$

$\kappa_\phi \sim O(1)$: energy fraction into ϕ

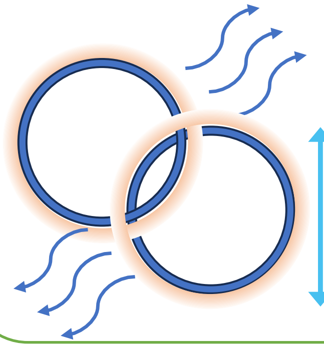
} Ω_{gw} from sound wave $\propto \kappa_{sw}^2 (H/\beta_{col})^2$

→ less important in the present case

SGWB from Bubble collision & baby BH constraints

- SGWB from Bubble collision

$$\Omega_{gw}h^2 \sim 10^{-5}\left(\frac{H_{col}}{\beta_{col}}\right)^2\left(\frac{\kappa_\phi \alpha_{col}}{1+\alpha_{col}}\right)^2 \text{ with } f \sim 10^{-3}\left(\frac{\beta_{col}}{H_{col}}\right)\left(\frac{T_{col}}{10\text{TeV}}\right)$$



- In our scenario: $\beta_{col}/H_{col} \simeq 3$

diluted plasma → less friction: $v_w \sim 1$

$\kappa_\phi \sim O(1)$: energy fraction into ϕ

} Ω_{gw} from sound wave $\propto \kappa_{sw}^2 (H/\beta_{col})^2$

→ less important in the present case

- PBH parameters: $M_{PBH,i}, \beta_{PBH} \simeq \epsilon(t_i)$ → $T_{col}(M_{PBH,i}, \beta_{PBH})$ from $\epsilon(t_{col}) = 1$

Order estimate of $\alpha_{col} \equiv \rho_{rad}(T_{col})/\rho_{vac}$ for $t_{nuc} \ll t_{col}, t_{ev}$ (t_{ev} : BH evaporation time)

(curvature of $V(\phi)$) $\sim \rho_{vac}^{-1/4}$ ⟺ $r_{PBH}(t) \sim M_{PBH,i}/M_{Pl}^2$ → $\alpha_{col}(M_{PBH,i}, \beta_{PBH})$

※ $t_{nuc} \sim t_{ev} \ll t_{col}$ may also be possible if Γ enhanced by the BH thermal effect

- Constraints on α_{col} from baby BHs

PBH constraints on $(M_{PBH,i}, \beta_{PBH})$ → also for baby BHs!

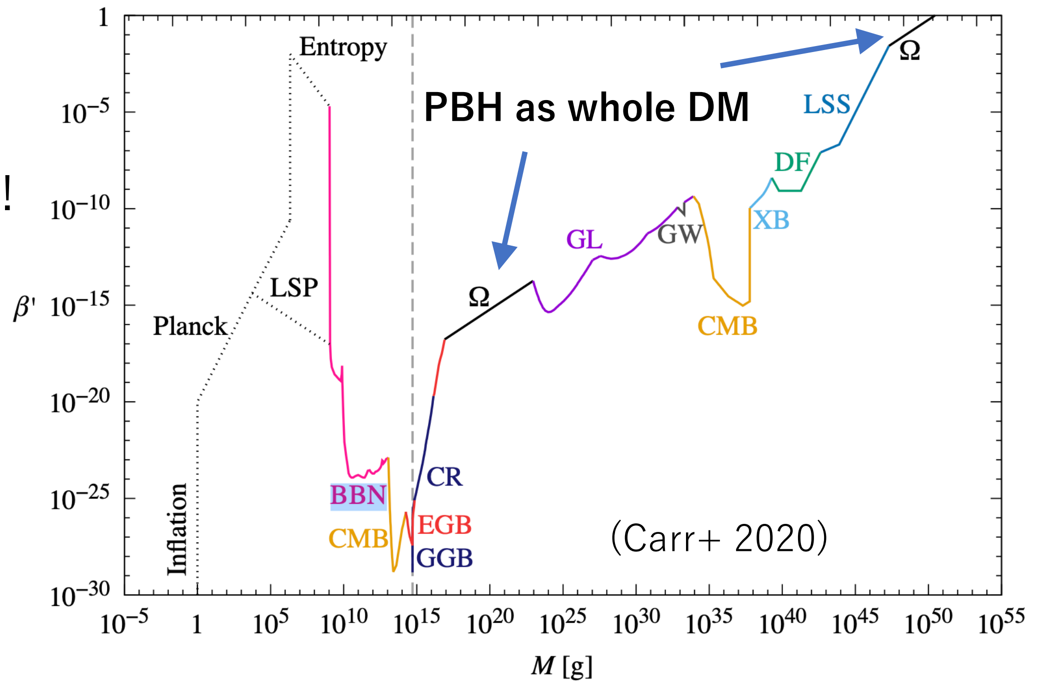
Avg. number of PBH per Hubble vol.: $N_{PBH} \sim \alpha_{col}^{-3/4}$

Prob. for patch **not containing PBH**: $P \simeq e^{-N_{PBH}}$

(Poison statistics assumed)

$$\beta_{bBH} \sim \rho_{bBH} 3M_{Pl}^2 H_{eq}^2 = P = \exp(-\alpha_{col}^{-3/4})$$

mass: $M_{baby} \sim M_{pl}^2 H_{eq}^{-1} \sim M_{pl}^3 \rho_{vac}^{-1/2} (M_{PBH,i})$



- Constraints on α_{col} from baby BHs

PBH constraints on $(M_{PBH,i}, \beta_{PBH})$ → also for baby BHs!

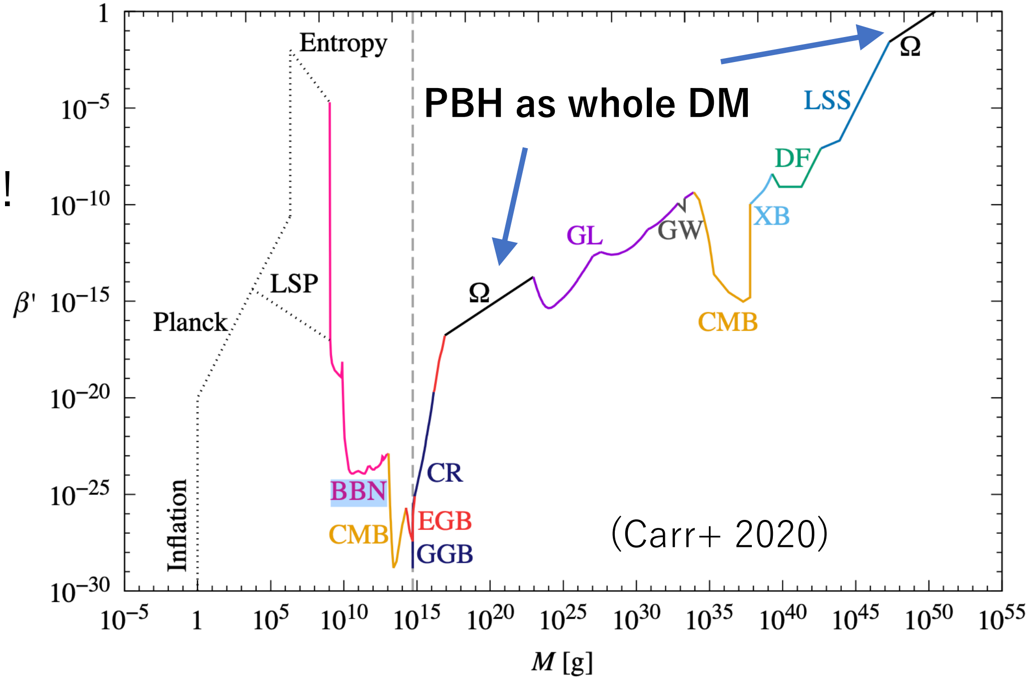
Avg. number of PBH per Hubble vol.: $N_{PBH} \sim \alpha_{col}^{-3/4}$

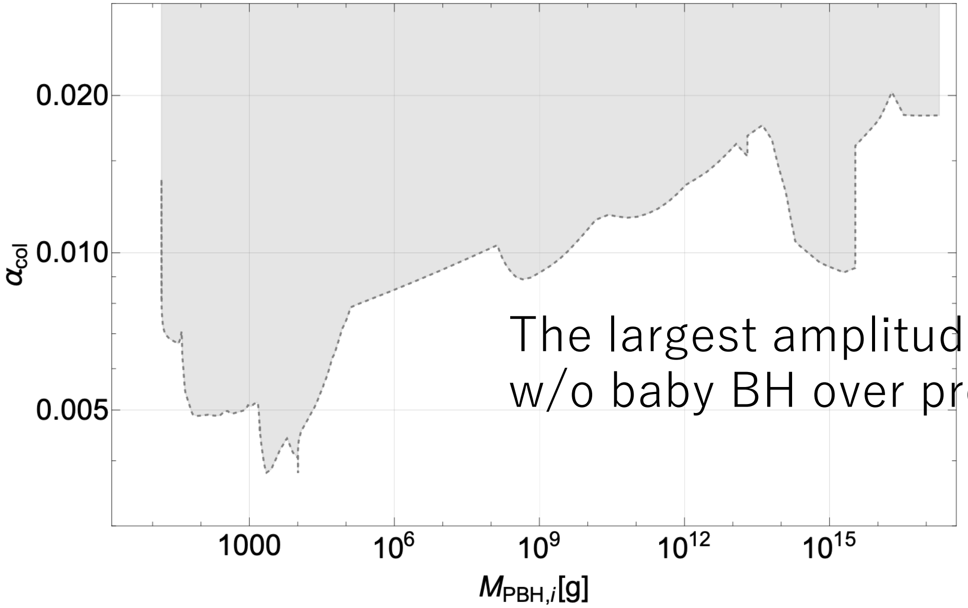
Prob. for patch **not containing PBH**: $P \simeq e^{-N_{PBH}}$

(Poison statistics assumed)

$$\beta_{bBH} \sim \rho_{bBH} 3M_{Pl}^2 H_{eq}^2 = P = \exp(-\alpha_{col}^{-3/4})$$

mass: $M_{baby} \sim M_{pl}^2 H_{eq}^{-1} \sim M_{pl}^3 \rho_{vac}^{-1/2}(M_{PBH,i})$





The largest amplitude
w/o baby BH over production

- Constraints on α_{col} from baby BHs

PBH constraints on $(M_{PBH,i}, \beta_{PBH})$ → also for baby BHs!

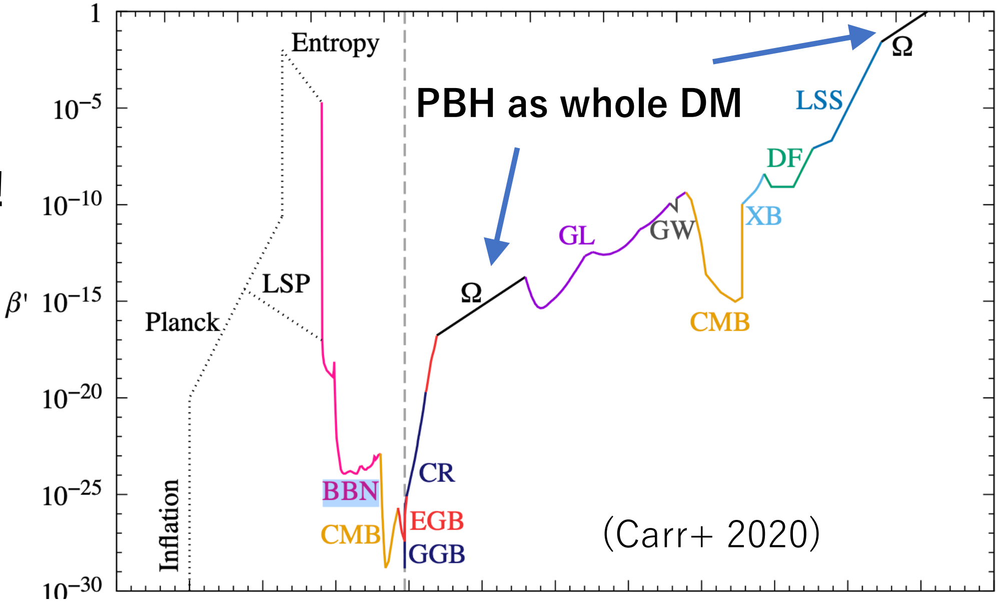
Avg. number of PBH per Hubble vol.: $N_{PBH} \sim \alpha_{col}^{-3/4}$

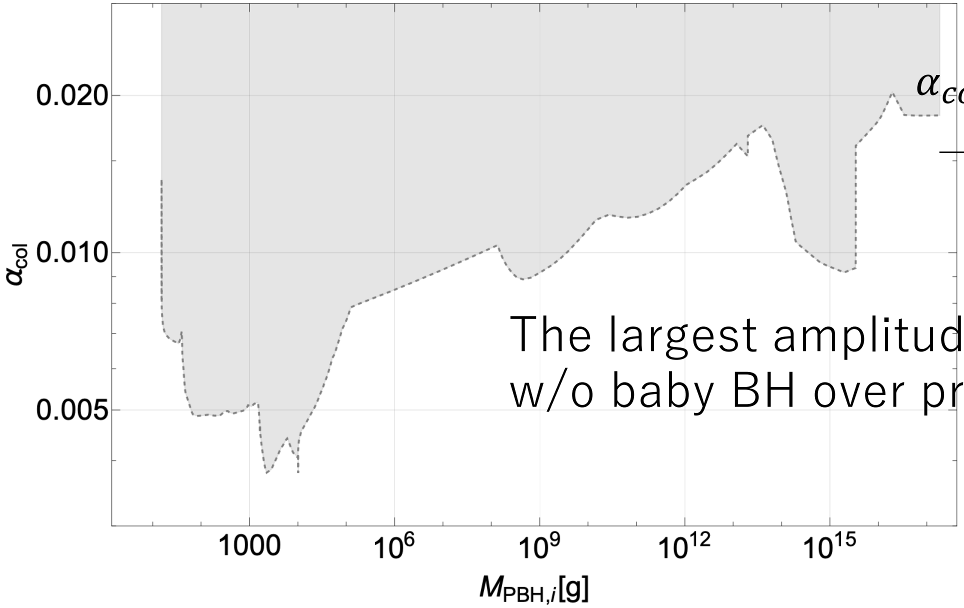
Prob. for patch **not containing PBH**: $P \simeq e^{-N_{PBH}}$

(Poison statistics assumed)

$$\beta_{bBH} \sim \rho_{bBH} 3M_{Pl}^2 H_{eq}^2 = P = \exp(-\alpha_{col}^{-3/4})$$

mass: $M_{baby} \sim M_{pl}^2 H_{eq}^{-1} \sim M_{pl}^3 \rho_{vac}^{-1/2} (M_{PBH,i})$

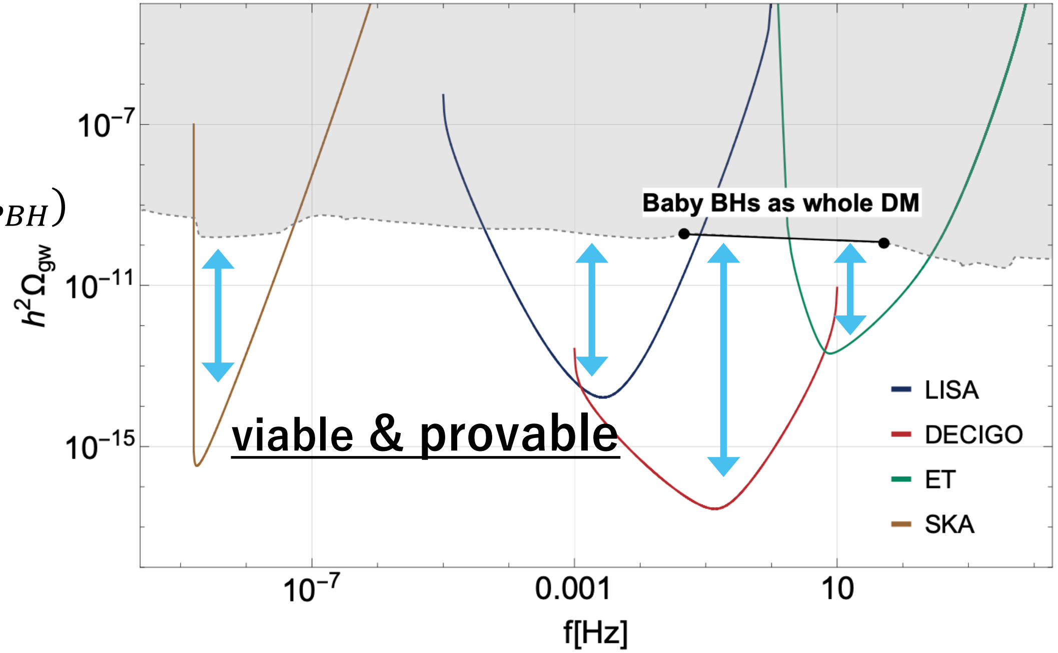




$\alpha_{col}(M_{PBH,i}, \beta_{PBH})$

$\to T_{col}(M_{PBH,i}, \beta_{PBH})$

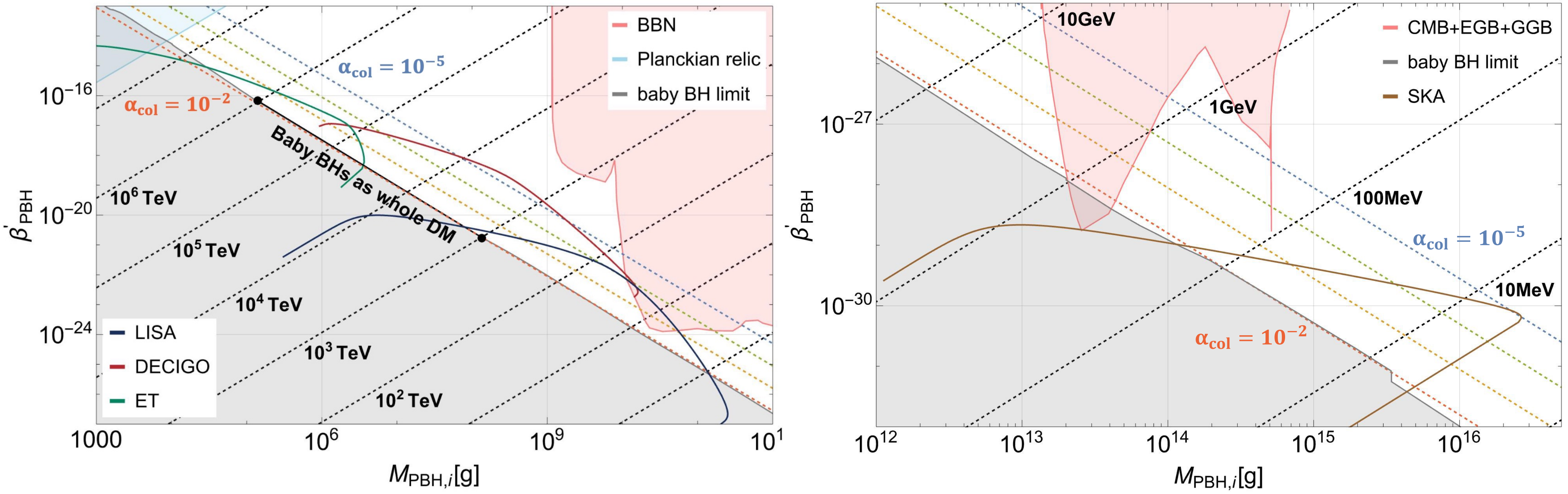
The largest amplitude
w/o baby BH over production



- A window of our scenario in PBH parameter space

$T_{col}(M_{PBH,i}, \beta_{PBH})$
$\alpha_{col}(M_{PBH,i}, \beta_{PBH})$ → Contours of T_{col}(black) & α_{col}(colored) (lower left bounded by baby BHs)

$(\Omega_{gw}(\alpha_{col}), f(\alpha_{col}, T_{col}))$ → Projection of sensitivity curves



SGWB observable with future detectors & DM abundance explained!!

※Recent PTA data favors $\alpha \sim O(1)$, which is prohibited by baby BH constraint…

Contents

- ➢Cosmological FOPT & gravitational waves
- ➢Sparsely distributed PBHs as impurities
- ➢SGWB from bubble collision & baby BH constraints
- ➢Summary & Discussion

Summary

- Compact objects gravitationally enhances the tunneling rate.

Primordial Black Holes may act as the nucleation sites.

- Smallness of number of PBHs per horizon volume at nucleation

  → **Horizon size bubble collision (→ SGWB) + baby BH production**

- Baby BH abundance ↔ PT strength α_{col}

→ Baby BH as whole DM with moderate value of α_{col}

→ DM explanation at the same time producing observable SGWB!!

Discussion

- Feasible particle physics model…?

FV-TV structure needs to be maintained during slow PT.

Dark sector physics? Vacuum tr. with zero-temperature potential…?

- Other types of impurities?

Compact objects: monopoles, Q-balls, oscillons, … work similarly

Defects network −spatial distribution of nucleation cite?

- Improving SGWB spectrum evaluation

For precise evaluation, cosmological expansion needs to be taken into account.

January 19th, 2024

A fate of catalyzed first order phase transition -black holes from primordial black holes-

TAsP meeting @ Università di Torino

Università degli Studi di Padova

Jun'ya Kume (UNIPD, INFN, RESCEU)

INFN Padova
Istituto Nazionale di Fisica Nucleare
Sezione di Padova

Research Center for the Early Universe
The University of Tokyo
RESCEU

Based on arXiv:2310.06901 [hep-ph] (to appear in PLB)

with Ryusuke Jinno (RESCEU), Masaki Yamada (Tohoku U.)